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Published in:
Journal of Hydroinformatics

DOI (link to publication from Publisher):
[10.2166/hydro.2018.133](https://doi.org/10.2166/hydro.2018.133)

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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Tuyls, D. M., Thorndahl, S. L., & Rasmussen, M. R. (2018). Return period assessment of urban pluvial floods through modelling of rainfall–flood response. *Journal of Hydroinformatics*, 20(4), 829-845.
<https://doi.org/10.2166/hydro.2018.133>

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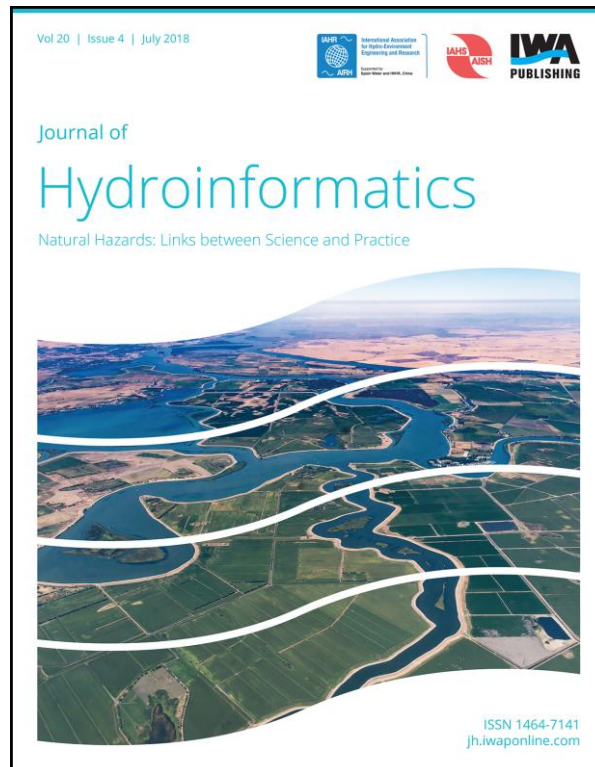
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Return period assessment of urban pluvial floods through modelling of rainfall–flood response

Damian Murla Tuyls, Søren Thorndahl and Michael R. Rasmussen

ABSTRACT

Intense rainfall in urban areas can often generate severe flood impacts. Consequently, it is crucial to design systems to minimize potential flood damages. Traditional, simple design of urban drainage systems assumes agreement between rainfall return period and its consequent flood return period; however, this does not always apply. Hydraulic infrastructures found in urban drainage systems can increase system heterogeneity and perturb the impact of severe rainfall response. In this study, a surface flood return period assessment was carried out at Lystrup (Denmark), which has received the impact of flooding in recent years. A 35 years' rainfall dataset together with a coupled 1D/2D surface and network model was used to analyse and assess flood return period response. Results show an ambiguous relation between rainfall and flood return periods indicating that linear rainfall–runoff relationships will, for the analysed case study, be insufficient for flood estimation. Simulation-based mapping of return periods for flood area and volume has been suggested, and moreover, a novel approach has been developed to map local flood response time and relate this to rainfall characteristics. This approach allows to carefully analyse rainfall impacts and flooding response for a correct flood return period assessment in urban areas.

Key words | flood return period, pluvial floods, rainfall–flood response, urban drainage system modelling

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INTRODUCTION

Urban drainage systems are most often designed with a specific return period or frequency of exceeding the maximum capacity. In principle, this means that for rainfall loading with a higher return period than designed for, a surcharging of the system is possible, leading to potential flooding of urban areas. According to the European Standard [DS/EN752 \(2017\)](#): *Drain and Sewer systems outside buildings*, simple design methods for drainage systems can be based on the *design storm frequency* for surcharging of the systems. For residential areas, this is, for example, recommended to be 1 in 2 years (i.e., a return period of 2 years). Thus, it is assumed that the return period of

exceeding capacity is related to the return period of the design storm, i.e., the rainfall. In EN 752 it is recommended to use *intensity–duration–frequency* (IDF) relationships (e.g., [Madsen et al. 2009](#)) for the particular area in question. The design rainfall, that a specific part of the system should comply with for a specified return period, is thus defined by estimating the maximum rainfall intensity corresponding to the most critical rainfall duration of a point in question, e.g., following the Rational Method ([Kuichling 1889](#)). This assumes steady flow conditions and a linear relations between rainfall intensity and design flow at a specific point of the system, the contributing area being its gradient. The design flow can be used in simple systems to determine pipe dimensions under the assumption of uniform flow conditions, i.e., that backwater effects, pressurized pipes, etc. must not occur.

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For more complex urban drainage systems, e.g., with branched drainage systems, overflow structures, backwater effects and which might be pressurized due to capacity limits, EN 752 acknowledges that the simple design solutions are inadequate and more advanced methods such as simulation models are required. Using these more complex methods, it is possible to estimate flooding of systems rather than just surcharging. Analysis of flooding consequences as an element for design leads to other criteria in terms of return periods for exceedance. EN 752 thus recommends a return period of 20 years of flooding of residential areas. It is evident here, that it is the return period of the flooding and not of a design storm. Therefore, their resulting effects have been investigated in detail in this study.

Estimating the return period of urban flooding at a single specified point based on the return period of the rain might be a difficult task. Due to the complexity of a flood where water flows both in the drainage system, surcharges the drainage system, as well as flows on the surface to depressions in the terrain, there might be a non-monotonical increasing relation between the rain intensity and the maximum water level in a given point. Other hydraulic structures causing flow irregularities such as pumps, weirs, gates, retention basins, etc., in the drainage system and preferential flow paths and ponding on the surface will exacerbate these non-monotonicities even more. Complex relationships between the rainfall intensity and the flooding response cause the return period of the rain intensity not necessarily to be equal to the return period of the flooding, as it is assumed in the simple design methods (e.g., Wright *et al.* 2014). Estimating the return period of flooding from historical rainfall records therefore requires detailed analysis of the rainfall–flood response; see e.g., Berggren *et al.* (2013) and Hlodversdottir *et al.* (2015) for use of design storms for flood modelling.

The European Floods Directive (EC 2007) recommend the European member states to produce flood risk assessment and flood risk maps showing a likelihood of flooding, e.g., corresponding to 100 year return periods. Using historical rainfall records to estimate the flood-response of a 100 year event will often be too difficult for three reasons:

1. As Djordjević *et al.* (2005), Maksimović *et al.* (2009) and Mark *et al.* (2004) state, long-term rainfall time series from this and the previous century might be non-

stationary due to climate change, that is, the frequency (or return period) changes over time (see also Ntegeka & Willems (2008) and Willems (2013a)).

2. Accurate projection of how climate changes will impact the 100 year return period in the future climate might be a difficult task (e.g., Willems *et al.* 2012; Thorndahl *et al.* 2017b).
3. High temporal resolution rain series are often unavailable for periods more than less than half a decade (e.g., 37 years in Denmark; Madsen *et al.* 2017). There are, however, exceptions, for example, in Belgium, where a continuous series has been measured at the same location over 100 years (Willems 2013b).

Some of these problems might be the reason that design storms have become popular. Design storms can be based on extrapolation of rainfall statistics to estimate return periods with a longer return period than the series contains, and easily be multiplied to a climate factor to represent future conditions (e.g., Arnbjerg-Nielsen *et al.* 2015).

In order to investigate the return period of flooding based on historical rainfall series, we will in this paper perform a modelling experiment on a Danish case study area in Lystrup, Denmark. With the intention to estimate the return periods of flooding, we will investigate the three following statements:

1. *Estimation of flood return periods cannot be accomplished without applying complex coupled 1D/2D models accounting for the interaction between rainfall, drainage system, potential runoff from rural catchments, and surface as well the flow dynamics.*

This is investigated by estimating return period of floods at catchment scale (Lystrup), by using an integrated urban drainage and natural stream model (1D) as well as a flood model (2D) with inputs from historical rainfall series, where the obtained results will be inter-compared and analysed in detail.

2. *It is necessary to include the temporal dynamics associated with rainfall in the estimation of flooding hence design storms based on fixed return periods will be inadequate.*

This is tested by studying the rainfall response locally by estimating the local flood response time in flood-prone areas. The local flood response time acts as a

surrogate measure of the concentration time and is estimated by correlating rainfall intensities aggregated over different durations with local flood water levels.

3. *The concept of the return period of flooding at a single point does not make much sense in complex systems. Instead, return periods should be linked to flood area extent, flood volume, etc.*

The third statement has already been introduced by McRobie *et al.* (2013), Ochoa-Rodriguez *et al.* (2015) and Simões *et al.* (2015). In this study, this is investigated by analysing, on the one hand, the flood return period statistics for each flood-prone cell of the urban drainage system and, on the other hand, local response time in flood-prone areas has been correlated with its corresponding maximum flood water level. These two approaches allow a broader overview, perhaps increasing the quality of the results when a flooding assessment is performed under a local perspective.

The paper is structured as follows. Next is a methodology section where the case study is presented. After that, the available precipitation data and their further selection process are described and then the complete 1D/2D surface flood model used for this study is introduced. The obtained results are described and analysed. First, flood return periods are assessed at catchment scale, then the temporal dynamics of rainfall are analysed at local flooding areas, followed by analysis of results of the local flood return period assessment. Discussion and several aspects of rainfall and urban pluvial flood modelling are considered followed by the final conclusions.

METHODOLOGY

Case study

The urban drainage system is located in Lystrup, close to Aarhus, in Denmark. It consists of a separate system (storm water), covering an area of about $875 \times 10^4 \text{ m}^2$, and serving a population of approximately 10,300 inhabitants. The area also has a small river system east of the catchment, and has an overall slope of 0.015 m/m. The system is mainly branched and its slope is not regular all over the study area so steep areas can be found together with flat regions. Terrain heterogeneity may have an influence on water

dynamics, especially when flooding occurs. The main slope direction however, is from NW (high elevation) to SE (low elevation). The catchment has been chosen since it has suffered the impact of several floods due to extreme rainfall in recent years, e.g., 26 August 2012 and 13–14 July 2014 (Thorndahl *et al.* 2016).

Precipitation data

In this study, a 35 year long rainfall measurement dataset (1979–2015 with minor disruptions) from two different rain gauges has been assembled. The rain gauges are operated by the Danish Wastewater Pollution Committee together with the Danish Meteorological Institute (DMI), and are part of a network of ~150 different rain gauges spread all over the country (e.g., Madsen *et al.* 2009). Both are tipping bucket rain gauges measuring at 1 minute frequency and are located close to the study area (Egaa ~6 km, 1990–2015; Viby ~16 km, 1979–1990).

Since the purpose of this study is to analyse urban flood during extreme rainfall, the two rain gauge measurement records were combined in a single dataset, filtering out dry weather periods and rainfall events with a cumulative depth lower than 10 mm. Events are separated by at least 1 hour with no recorded rain in the tipping bucket rain gauges. One could argue for the use of a larger minimum inter-event time in order to allow for coupled rainfall events leading to single runoff events. However, since we focus on relatively rare events, with return periods larger than 1 year, this criterion has no practical implication. Potential spatial variability of rainfall within the catchment has been neglected throughout this study.

Rainfall event selection

The selection of the most severe flood-producing rainfall events is performed through a two-step multi-criteria method. First, a rainfall–runoff simulation of the urban drainage system is carried out for the complete historical rainfall dataset from which a list of events is pre-selected. This first filtering is performed through the inter-combination of two criterions: (1) threshold, defined as the exceedance of a given runoff flow (characterized as the total inflow from the catchment to the

drainage system); and (2) duration, defined as the amount of time that runoff surpassed the defined threshold.

A matrix of six different thresholds ($1 \text{ m}^3/\text{s}$; $2 \text{ m}^3/\text{s}$; $5 \text{ m}^3/\text{s}$; $11 \text{ m}^3/\text{s}$; $16 \text{ m}^3/\text{s}$; $22 \text{ m}^3/\text{s}$) and five different durations (1 min; 5 min; 10 min; 30 min; 60 min) is applied using the long term simulations module (LTS) found in MOUSE modelling packages (see, e.g., [Schaarup-Jensen et al. \(2009\)](#) and [Thorndahl \(2009\)](#)). Both the threshold and duration values of the rainfall selection matrix are chosen in accordance with the results obtained from the complete rainfall–runoff simulation. Hence, the selection matrix can guarantee an appropriate rainfall variability both in terms of intensity and in terms of depth. As a result, 143 rainfall events are pre-selected from the catalogue of 333 events with total depths larger than 10 mm. The inter-combination matrix between thresholds and durations includes different rainfall types, from extreme high peak storms with a short duration to more moderate rainfall with longer duration.

The final step for rainfall event selection implies the hydraulic network simulation of the 143 pre-selected rainfall events. From the obtained results, focus is placed on the number of surcharged manholes in the urban drainage system (defined as water exceeding ground level). The 35 events with the highest number of surcharged manholes are selected for the final rainfall event list used in this study ([Table 1](#)).

The selection of 35 events for a 35 year period enables us to analyse data for a return period of up to 1 year. This is obviously under the assumption that no events with higher return periods than 35 years have been measured during the observation period. [Arnbjerg-Nielsen et al. \(2002\)](#) recommend considering no more than a quarter of the total period of a rain series for valid return period assessment in urban drainage modelling. Since, in this study, only relative comparisons between rainfall and rainfall response are considered, potential errors estimating the real return periods are neglected. Furthermore, it is assumed there is no climate change impact on the frequency of events and thus the return period assessment.

Urban flood model

A complete 1D/2D semi-distributed model of the study area has been provided by Aarhus Vand (Aarhus Water Utility

Table 1 | Data of 35 events with the highest number of surcharged manholes

Event # rank	Rp ^a (years)	Date (dd-mm-yyyy)	# SM ^b	Max. intensity (over 1 min) (mm/h)	Total depth (mm)
1	35.00	27-06-2007	474	84.00	43.80
2	17.50	08-06-1996	473	168.00	17.00
3	11.67	24-08-1997	364	120.00	32.00
4	8.75	01-08-2006	344	108.00	56.20
5	7.00	05-05-2015	331	108.00	17.20
6	5.83	17-06-1981	293	132.00	13.60
7	5.00	07-08-2005	290	84.00	33.20
8	4.38	12-08-2006	287	108.00	21.00
9	3.89	28-07-2001	278	96.00	11.20
10	3.50	24-07-1997	270	84.00	15.00
11	3.18	27-07-2013	267	174.00	12.80
12	2.92	14-07-2014	260	36.00	66.00
13	2.69	12-08-2002	255	84.00	34.80
14	2.50	10-06-1980	254	84.00	12.80
15	2.33	26-08-2012	245	108.00	51.60
16	2.19	08-08-1979	242	96.00	14.40
17	2.06	25-08-1995	234	84.00	13.80
18	1.94	17-08-2001	226	120.00	16.80
19	1.84	22-08-2012	225	96.00	25.20
20	1.75	18-08-1994	211	72.00	19.60
21	1.67	02-09-1979	205	84.00	36.80
22	1.59	19-09-2007	196	132.00	19.00
23	1.52	17-07-1986	188	60.00	16.20
24	1.46	08-06-2003	186	120.00	20.40
25	1.40	12-07-2010	180	72.00	11.00
26	1.35	17-08-2000	168	84.00	16.60
27	1.30	15-07-2005	167	84.00	11.40
28	1.25	06-09-1995	164	72.00	15.80
29	1.21	24-08-2015	161	84.00	13.20
30	1.17	29-06-1994	143	60.00	17.80
31	1.13	02-06-2014	142	84.00	19.00
32	1.09	18-06-2002	140	144.00	22.80
33	1.06	13-09-2001	133	84.00	21.00
34	1.03	25-06-2007	131	96.00	37.60
35	1.00	31-07-2005	129	72.00	14.80

^aRp, return period in years.

^b#SM, number of surcharged manholes (water level above ground level).

Service). The model is built using MIKE modelling packages from DHI ([DHI 2014](#)). Surface-runoff routing to the drainage system is solved by a time–area surface-runoff package,

integrated in MIKE Urban. Hydraulic modelling of the urban drainage system has been carried out with MIKE Urban, solving dynamically the 1D Saint-Venant equations (DHI 2014). The model setup consists of 3,247 subcatchments covering an area of 872 ha with 2,179 nodes (representing manholes) and 2,180 links (pipes) spread over 70 km within the catchment area. The model also contains 18 storage basins and eight outlet discharge points.

The model includes runoff from impervious surfaces based on detailed land register information defining roofs, roads and other paved areas as impervious. This layout of the model is normally applied to analyse system capacity up to a return period of 5 years (since the recommended return period of surcharging manholes to ground level is 5 years for separate water systems in Denmark; WPC 2007). In order to account for runoff from green and pervious surfaces to the drainage system and the stream, this layout of the model has been extended by a model estimating the runoff from these surfaces. This model was built by Løvgaard (2016) independently from the MIKE Urban model and is based on a modified version of Horton infiltration (Akan 1993). It is based on standard parameters for clayey subsurfaces, which are present in Lystrup.

The sub-catchments modelled with runoff from impervious areas only are shown as urban catchments in Figure 1 (with minor exceptions for some green areas in some parts of the town which are modelled as pervious, not shown). Correspondingly, the areas with runoff from pervious surfaces are shown as rural catchments in Figure 1.

The overland flow modelling is carried out with MIKE Flood, a hydrodynamical surface flow model based on MIKE 21, able to solve the shallow water equations in a structured grid (DHI 2014). A digital terrain model (DTM) provided by the Danish Geodata Agency (GST), with a resolution of 2×2 m, is used as the topographical grid information for the surface flood modelling. Coupling between pipe-surface flow is performed through manholes rather than gullies or inlets, typically found in reality. Since it is a semi-distributed model, net rainfall-runoff is used as direct input into the urban drainage system and, therefore, surface flooding only occurs once manholes start surcharging. These simplifications and their consequent errors have been studied in detail by Fuchs & Schmidt (2015) and Pina et al. (2016), who highlight the importance of implementing

urban drainage surface data such as gullies/inlets onto the model when available. However for this study, there is no such available database that allows inclusion in the model. Furthermore, since this study applies to relative comparisons between different rainfall events and their consequent floods but always on the same model, their associated errors can be neglected. The model also includes a small section of a river stream of ~ 2.5 km, Ellebæk, located west of the study area and built in a series of river sections of about 3 m length all along the river. Apart from its base flow of $0.015 \text{ m}^3/\text{s}$, the river also receives discharge waters from drainage areas adjacent to the river system. Finally, the river is also coupled with the overland surface model so any flood caused by river overflow will also be considered. Figure 1 shows a layout of the model described above with distinction of the catchments considered as rural, contributing both to the river system but also directly to the urban drainage system in the urban catchments.

The urban flood model has been developed and supplied by Orbicon (engineering consultant company) for Aarhus Water Utility Services. The model development and build up follows the Danish operation practices for drainage systems under rain (Publication no. 27 of the Danish Water Pollution Committee; WPC 2007), which provides a series of recommendations and best practices for urban drainage model development. Publication no. 27 has been widely used in recent years as a practice for model development in the Danish water industry and it is considered as a good reference point for urban drainage model development since it allows producing models with sufficient quality for further exploitation, either at private industry or for research. In addition, Orbicon has performed a further adjustment of the urban flood model. This adjustment is based on a single high intensity rainfall event (26/08/2012) where several floods were observed and recorded by the local authorities and private citizens. The urban flood model adjustment consists of a refinement of the subcatchment runoff contributions to the urban drainage system and also adjustment of the runoff contribution from the pervious areas (which is normally not considered in Denmark). This has allowed the best setup to be obtained in terms of flood depths when compared to the footage and narratives of the flood-prone areas from local authorities and private citizens. Since the urban flood model is adjusted through a single

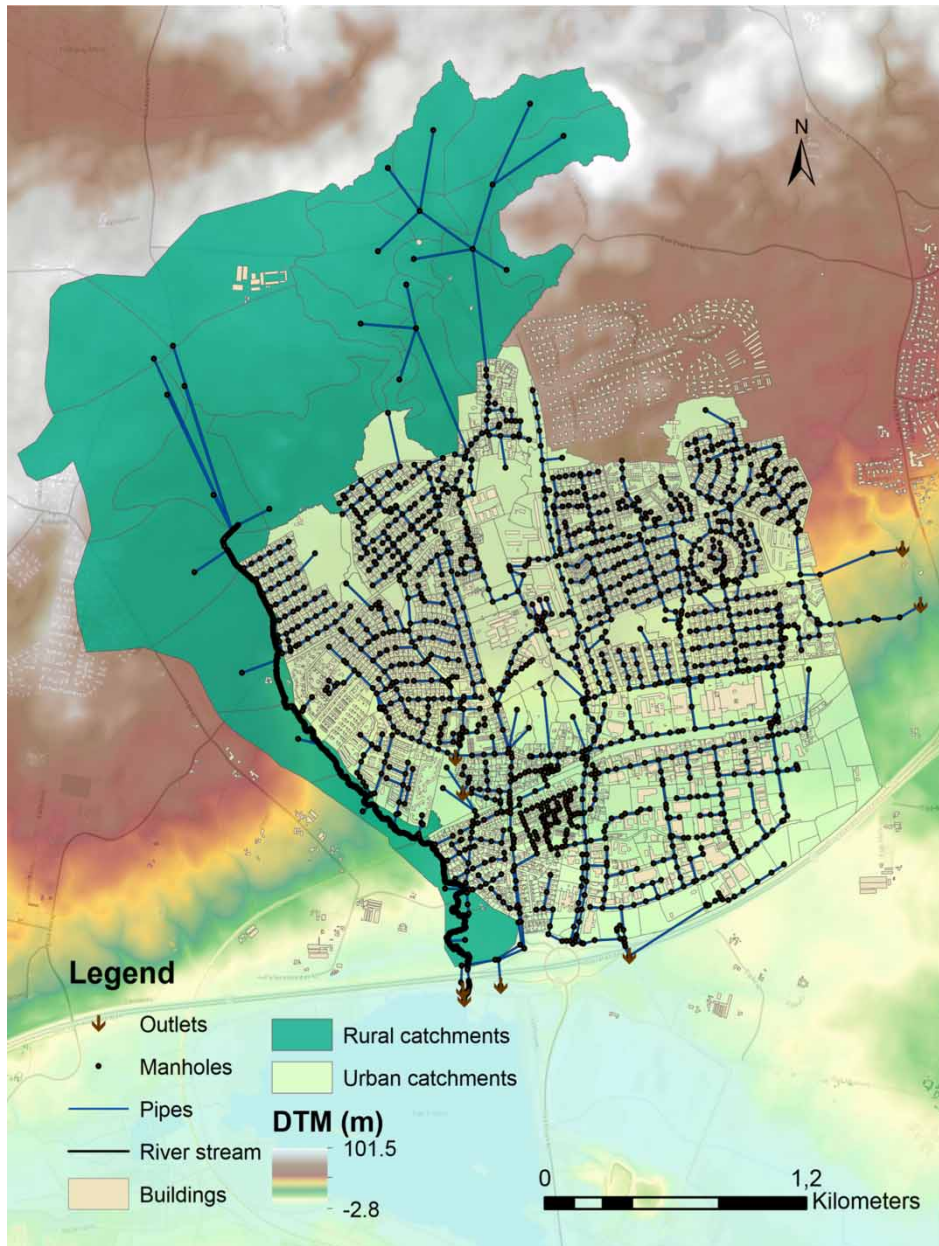


Figure 1 | Model layout of Lystrup urban drainage system area.

high intensity rainfall event, the simulation of other events less severe than the one used for the flood model adjustment might be overestimated, but again, since this study is based on relative comparisons, this is considered a minor issue.

In order to minimise model instabilities, simulations are performed with a calculation time step of 60 sec for rainfall-runoff, 5–60 sec for dynamic hydraulic calculations and 0.5 sec for 2D surface flood modelling. Return

periods are estimated ranking either rainfall intensities aggregated over different durations or flood response results using the California plotting position method (Rakhecha & Singh 2009).

For estimation of relationships between rainfall and flood response, the Spearman correlation coefficient (ρ) is used since it is not assuming linearity as is the case with a correlation parameter such as Pearson's r .

RESULTS

Flood return period assessment at catchment scale

Full 1D/2D simulations of the 35 selected rainfall events have been performed and results analysed with special focus on the observed flood area and flood volume. Figure 2 presents an example of the simulated results of event #15 (26/08/2012), in terms of maximum flood depth. This particular date has been chosen since there are several recorded instances of flood during this event. Flood depths under 0.002 m have been neglected and thus from >0.002 to 2 m were included. As seen in Figure 2(a), different flood-prone areas can be observed throughout the urban drainage system, both in low terrain areas, where surface water is expected to accumulate, but also in some upstream points, where water is retained in ponds. In addition, the river system receives the contribution of several urban drainage system discharge points which generate diverse areas where flood is also observed. The flood-prone area located at the most southern point on the map refer to Lake Egå Engsø, which receives the contribution of the river system. The lake is out of the boundary conditions for this study thus results observed in this specific area will not be considered further. Figure 2(b) illustrates a timeline of the main characteristics of rain and the simulated flood area and volume for that specific event. Note that flood results are separated between rural and urban areas; however, the latter are the main point of interest and will be analysed in major detail. Flood areas present higher values in urban areas ($\max \sim 6 \times 10^5 \text{ m}^2$) while for flood volumes, these are higher in rural catchments ($\max \sim 10 \times 10^4 \text{ m}^3$). These differences are mainly due to the river bed section profile, which does not generate extensive flood areas but allows larger amounts of water to be carried, and also to the model simplification at rural catchments, where water cannot easily enter the drainage system or the stream and therefore tends to pond on the surface.

Traditional 1D/1D flood modelling often considers the surcharging of manholes as an indication of flood (Maksimović et al. 2009). Although accurate flood modelling of urban drainage systems has evolved notably in the last years, manhole surcharging or urban drainage capacity exceedance are still used concepts in the design of urban

drainage systems. Figure 3 shows a comparative plot between the number of surcharged manholes (Figure 3(a)) and its corresponding observed flood area and volume for each of the simulated events (Figure 3(b) and 3(c)). The three plots are displayed following a decreasing order of number of surcharged manholes. Note that as in Figure 2, a distinction has been made between rural areas and urban areas. As can be seen, there is no clear relationship between the number of surcharged manholes and observed flood areas or volume. As also explained in Figure 2, urban flooded areas are in all cases larger than rural flood areas. Contrarily, flood volumes in rural areas present higher values when compared to urban catchments.

Comparing the three plots between each other, it is clear that the relationship between the decreasing ranked rainfall and flood area and volume is, in general, ambiguous although some similarities are found between flood area and volume, hence further analysis is needed in this direction.

Accordingly, Figure 4(a) shows the correlation between flood area and volume obtained from the simulated events for both rural and urban catchments. The gradient in a linear fit between the two, corresponds to the average (water level) in flooded cells. There is a clear difference between the two catchment types, the rural having a higher tendency to increase in flood volume rather than in area ($\rho = 0.99$), for as previously explained, flood water from rural areas tends to pond. This is mainly due to the simplification of rural catchments and their connectivity to the urban drainage system. Regarding the urban catchments, results are more scattered ($\rho = 0.73$), where smaller and larger events present a better correlation; however, middle ranged event results are more diverse and there is no clear correspondence between flood volume and area. Rain characteristics and unsteady response impacts on urban catchments are the main cause for the observed variability. As done with flood area and volume, their corresponding return periods have been scattered and presented in this case, in a log scale (see Figure 4(b)). Rural catchment results present a higher correlation coefficient when compared to urban catchments ($\rho = 0.99$). Complexity of rainfall and of the urban drainage system plays a key role in the differences found. Regarding the

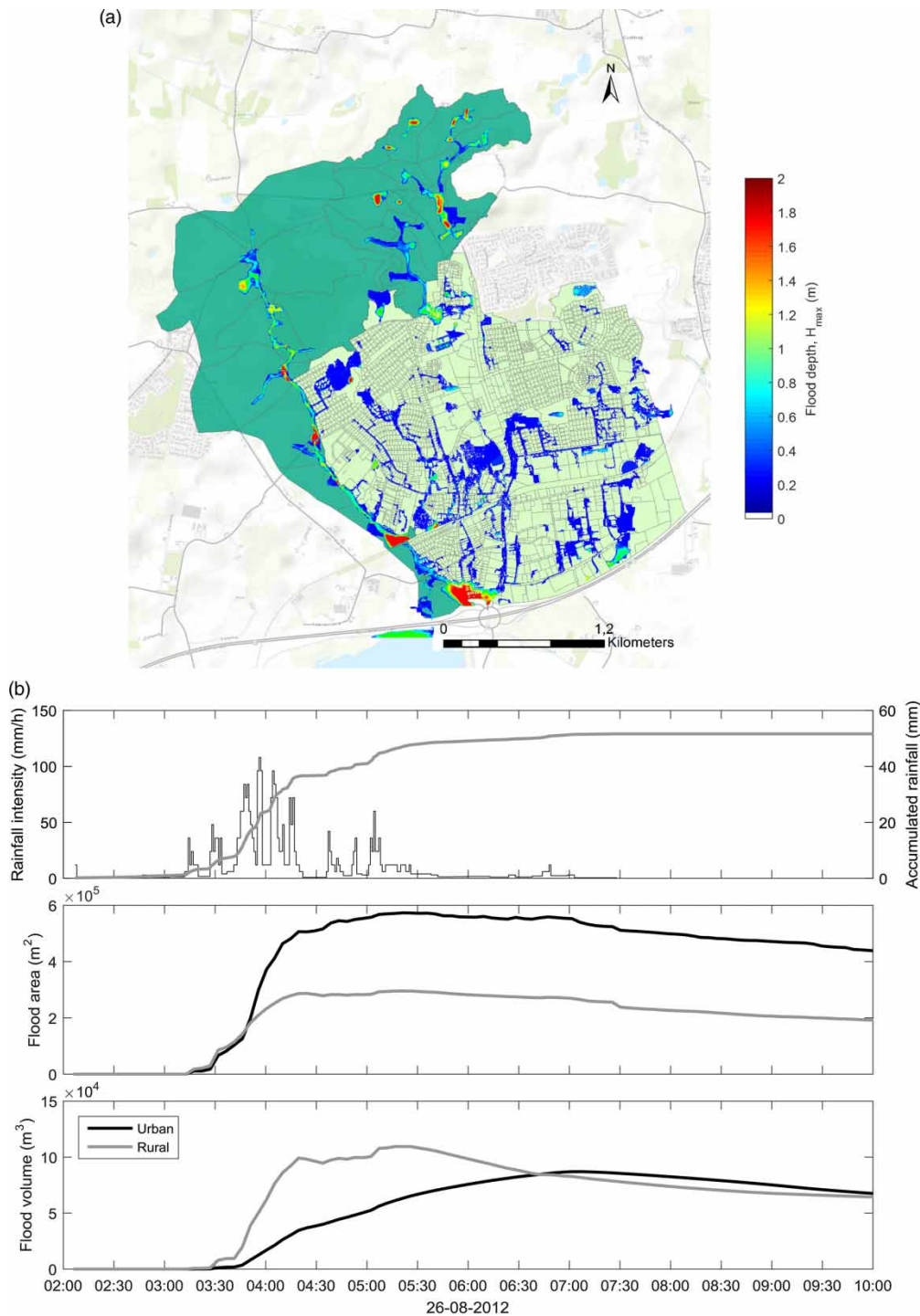


Figure 2 | (a) Maximum flood depth and (b) rainfall intensity and depth, simulated urban and rural flood area and volume for event #15, 26/08/2012.

urban correlation results, the obtained value is of $\rho = 0.75$, which can be considered as acceptable from a general viewpoint; however, return period values ranging from

approximately 3–20 years are more scattered, which highlights the necessity to consider both flood area and volume variables since they can both provide valuable

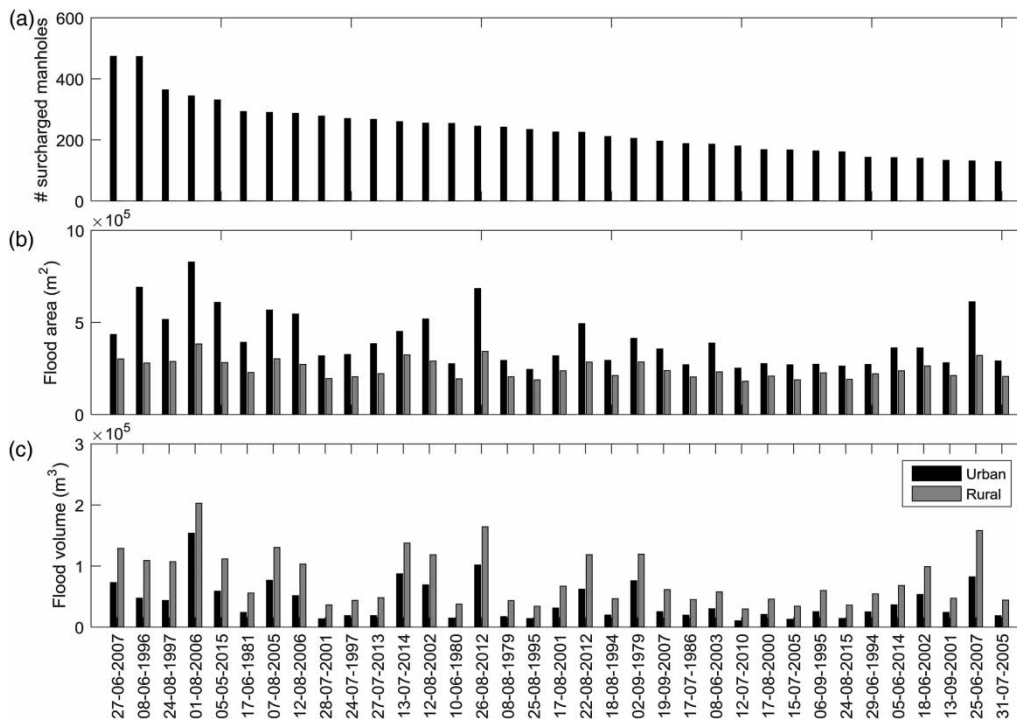


Figure 3 | (a) Number of surcharged manholes, (b) flood area and (c) flood volume obtained after the simulation of the selected rainfall events.

information in order to achieve precise and robust flood return period assessment results.

From the analysis performed in Lystrup at catchment scale, it is clear that the assessment of flood return period, either based on area or volume, cannot be accomplished without advanced 1D/2D coupled models, which allow representation of both detailed hydraulic and surface dynamics. In addition, flood area and volume and their corresponding return period estimates should both be considered separately in order to guarantee the quality of results. The variability between urban and rural areas indicates that the return period assessment is very dependent on the complexity of the system. In this case, the rural area behaves more predictably (partly due to the simplified approach defining rural catchments) than the urban area where the heterogeneity and non-linear rainfall runoff response of the drainage system can play an important role.

Temporal dynamics of rainfall at local flooding areas

As previously mentioned, the selection of rainfall events has been undertaken following a multi-criteria approach in

order to ensure appropriate rainfall variability. As different rainfall dynamics can generate different impact responses on the system, it is also interesting to investigate the relationship between rainfall and flood response locally. Following the steady-state assumption of the rational method, as described in the Introduction, there is an unambiguous dependency between the rainfall intensity over a specific duration and the water level at a point for simple systems. According to the rational method, the duration over which the rainfall intensity is averaged corresponds to the time of concentration. If an unambiguous relationship is present in a flood-prone cell, it is possible to use the rainfall duration as an estimate of the local flood response time to this specific flood-prone cell. In this section, it is investigated whether these assumptions for simple systems are valid for the studied catchment, or whether the flood response is too complex to develop simple relationships between the rainfall and the flood response.

From the 35 flood maps obtained after simulation, flood-prone areas have been outlined by selecting only the surface cells that have any recorded flood >0.002 m for at least 30/35 events (see Supplementary information, Figure S1,

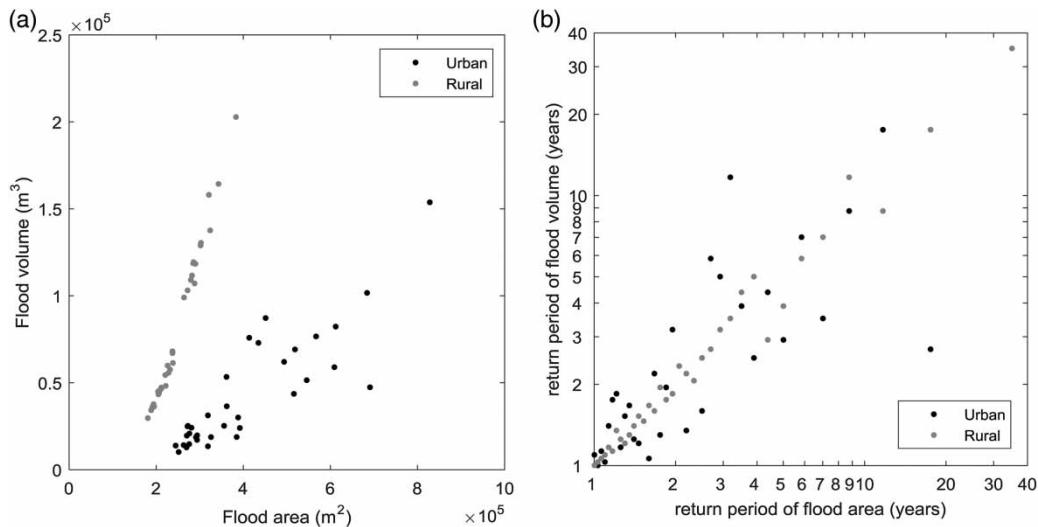


Figure 4 | Scatter plot between (a) flood area and flood volume for the simulated rainfall series and (b) return periods of flood area and flood volume.

available with the online version of this paper). As a result, a total of 108,923 cells (2×2 m) have been selected from a total of 3,500,212. For each flood-prone cell, the maximum flood level obtained per simulation has been correlated with the maximum rainfall intensity of a specific event at 1 min duration intervals (see Figure 5(b) and 5(d)). Note that the term ‘duration’ refers to the aggregation period and not to the length of an event. This procedure has been repeated for all 35 events’ varying rainfall durations from 1 min to 1,441 min (the latter being 1 day rainfall duration) and calculating its corresponding correlation coefficient. The varying rainfall duration has been chosen in order to ensure that all flooding water has been re-incorporated into the urban drainage system, hence it has been considered for the analysis. Thus, for each flood-prone cell, 1,440 scatter plots have been obtained per rainfall event (36,000 in total). Delineating the curve generated from all the obtained correlations (ρ) over the range of rainfall durations allows determination of the peak, which can be considered as an indicator of the local flood response time for a given flood-prone cell (Figure 5). Note that for a better understanding, two flood-prone cells, Point 1 and Point 2, both located in urban areas, have been exemplified in Figure 5.

Figure 5(a) and 5(c) illustrate how the local flood response time is found by searching for the highest correlation between the flood level (water level) and the rainfall intensity (averaged over different durations from 1 to

1,440 min). Figure 5(b) and 5(d) show scatter plots of the rainfall duration with the highest correlation which is assumed to be equal to the local flood response time at the point of interest. For Point 1, the maximum correlation ($\rho = 0.96$) is found at a duration of 139 min, while for Point 2 the maximum correlation ($\rho = 0.61$) is found for a rainfall duration of 32 min.

Based on the whole set of obtained correlations (ρ) for all flood-prone cells, a map is delineated highlighting the response time distribution and maximum correlation values (ρ) over the flood-prone areas of the urban drainage system under study (see Figure 6).

Analysing in detail the local flood response time flood map shown in Figure 6(a), the areas where the response times are longer are mainly located north of the drainage system, where rural catchments are found. Network complexity is limited in these areas, thus storm water connectivity to the urban system is low and consequently more sensitive to generating flood during extreme rainfall events. In addition, the terrain in these areas is rather flat so surface water tends to pond. In contrast, urban areas present, in general, short local flood response time, mainly caused by the presence of impervious catchments and to a better (and faster) connectivity to the drainage system. Moreover, flood-prone areas are shaped by the urban fabric, i.e., streets and larger roads, buildings or the main slope direction throughout the urban system. In contrast,

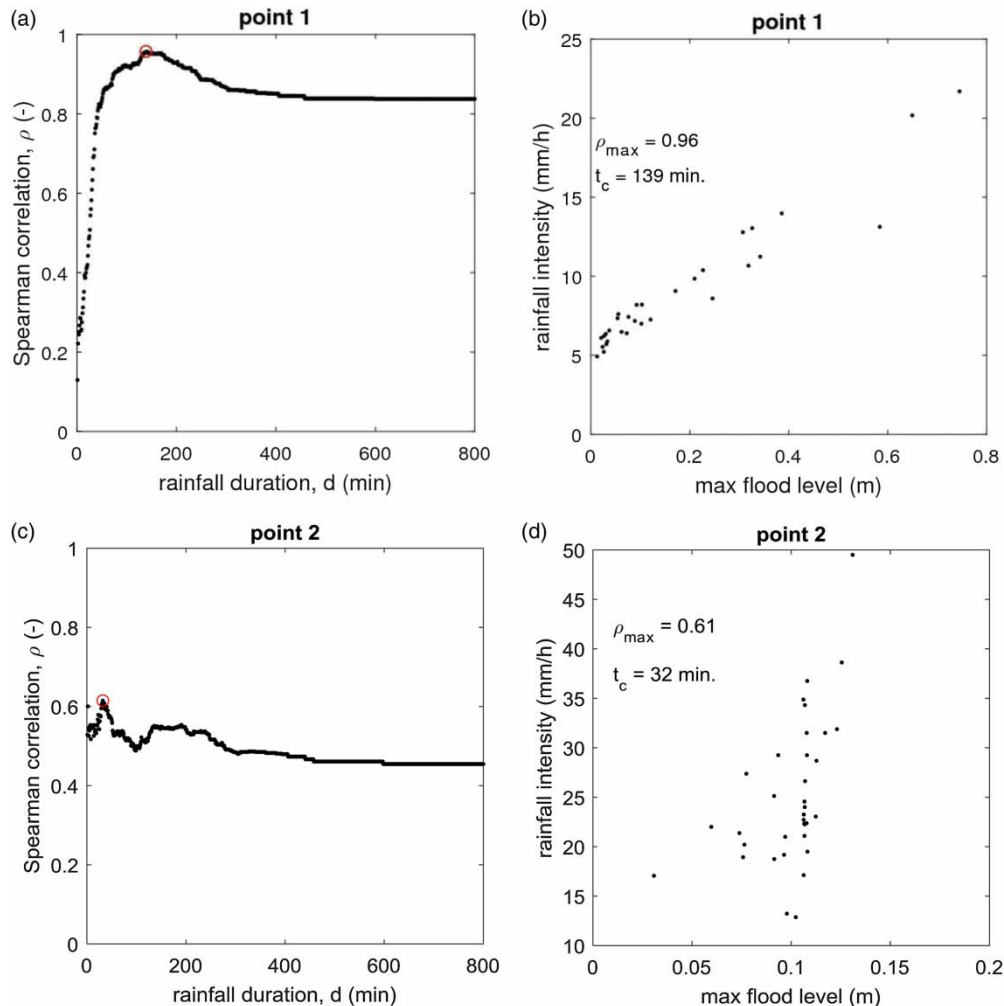


Figure 5 | (a) and (c) Spearman's correlation coefficient (ρ) vs. rainfall duration and (b) and (d) maximum correlation of flood level vs. rainfall intensity for Point 1 and Point 2.

flood-prone cells in urban areas with longer response times, are mainly caused by ponding surface water, originated at different locations. Thus, the complexity of urban drainage systems has a direct impact on the local flood response time estimation. The river system, which receives a part from the rural catchment contribution, and discharge water from urban areas, has in general low to medium response time. Simulation results show a tendency of an increasing local flood response time along the river system. As the river flows downstream from northwest to southeast direction, the number and volume of contributions from the urban drainage system to the river also increase, having a direct impact on the progression of the local flood response time results along the river stream.

Figure 6(b) illustrates the map of the obtained maximum Spearman's correlation coefficients for each of the flood-prone cells over a specific rainfall duration. The map allows evaluation of the level of consistency of the estimated local flood response time in Figure 6(a). Results show a strong correlation where the drainage system surcharges and water does not flow over the surface but tends to pond (e.g., Point 1). Additionally, correlation is weak-to-moderate for areas where there is a large transport on surcharging points (manholes), mainly due to the contribution of multiple surcharging manholes with diverse local flood response time. This is an indication of system complexity and thus an indication of departure from the assumption of a monotonically

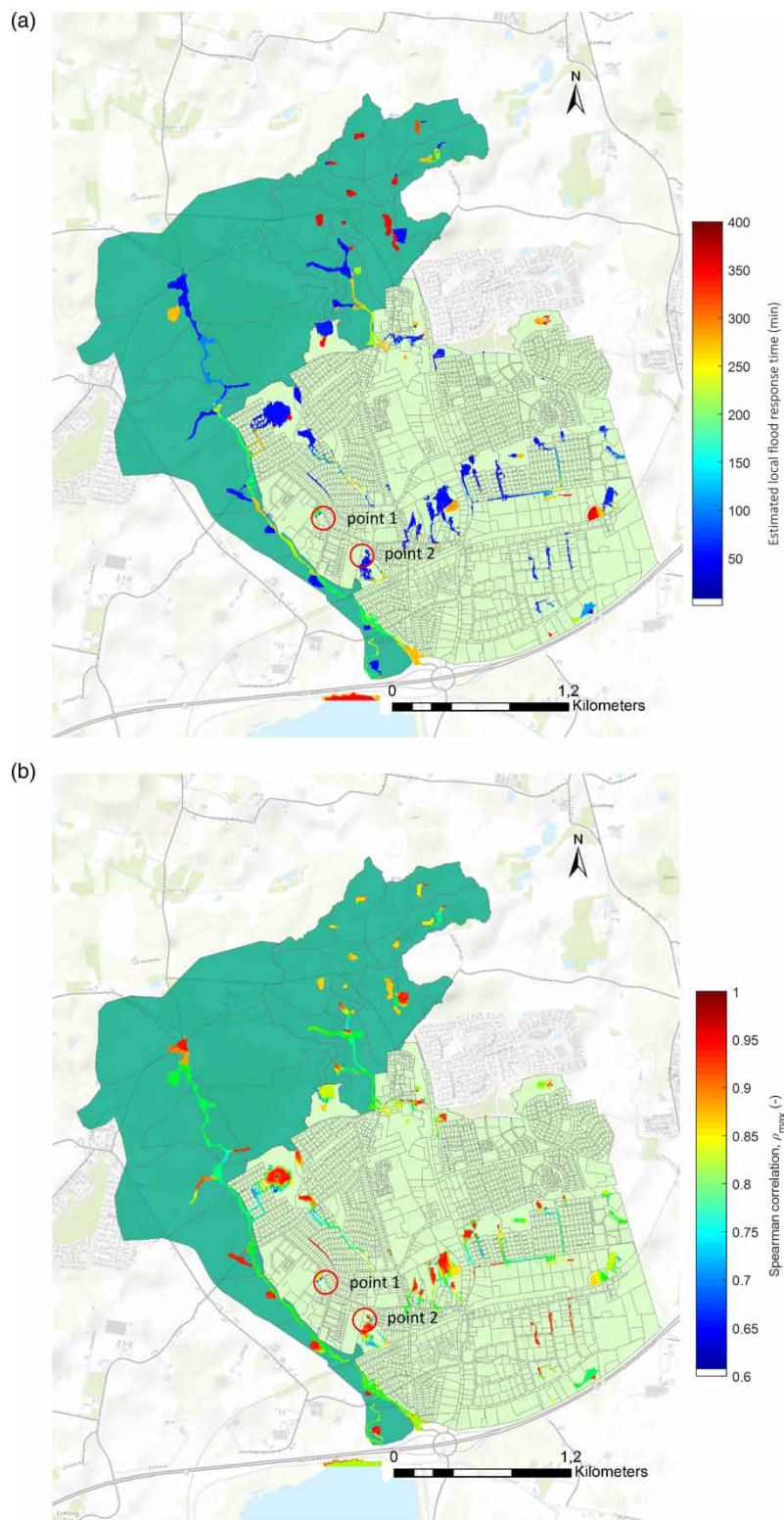


Figure 6 | (a) Local flood response time estimation map of flood-prone cells and (b) overall Spearman's correlation coefficient map.

increasing relation between the rain intensity and the maximum water level.

The estimation and mapping of the local flood response time for the overall study area has emphasized the variability that can be found in complex urban drainage systems. The assumption that design storms monotonically increase and have an unambiguous relationship between rainfall intensity and surface water level, can be considered as acceptable in areas where local flood response time is comparatively low. However, they are insufficient in areas with larger local flood response times, thus, design storms cannot be recommended in these cases.

Local flood return period assessment

In this section, the flood-prone cells delineated at Lystrup have been used to perform a local flood return period assessment. Flood water level results have been selected from highest to lowest and return period statistics for each flood-prone cell have been carried out. A map highlighting the return period for each cell has been built, based on a fixed water level (e.g., water level >0.1 m), i.e., in this case, the map shows the frequency (in years) that a certain cell will be flooding over 10 cm. This approach has the advantage of allowing multiple and adjustable return period flood maps depending on the desired water level. For example, a return period map can be built based on a water level >0 m (see Figure 7(a)); >0.10 m (see Figure 7(b)). Note that both figures have been built on a log scale for better representation of results.

Figure 7(a) represents the flood-prone cell return period map with a water level set over 0 m. It provides information on how often a flood will occur. Results show that, based on the applied rainfall dataset, the number of cells with a return period between 1 and 3 years is large, thus they are more likely to be flooded in comparison to other regions of the urban drainage system. Figure 7(b) represents the flood-prone cell return period map with a water level set over 0.1 m. In this case, the number of cells is reduced significantly; however, when compared to Figure 7(a), it also highlights the areas with larger demands for flood protection. Several flood-prone areas can be found, especially north of the study area, in rural catchments, which are mainly the consequence of water ponding. However,

similarities can also be found in urban catchments. Another spot of urban flood-prone cells, located at the junctions between rural and urban catchments, is caused by the direct contribution from rural surface water, which flows downstream following the natural terrain slope. Note that the river system appears flooded; however, only in some specific areas is there an actual flood, where the water level reaches the limits of the riverbed.

A supplementary statistical analysis was performed at the studied urban drainage system based on a combination of results obtained at the temporal dynamics of rainfall in local flooding areas section and the local return period assessment section, where the maximum water level return period for each flood-prone cell was correlated with the return period of rainfall intensity averaged over the duration found at the temporal dynamics of rainfall at local flooding areas section. Two different approaches have been applied in order to estimate the return period of the rainfall. The first one considers each of the 35 selected rainfall events only, while the second approach considers all events of the entire rainfall dataset of 35 years (see Figure 8(b)). These two approaches allow comparison of the results between the selected extreme rainfall events and the complete rainfall dataset.

Figure 8(a) shows the obtained statistics for Point 1, at a rainfall duration of 139 min. When considering exclusively the 35 selected events, the results present almost a linear correlation between water level return period and rainfall return period. When the whole rainfall dataset is considered, values are slightly biased and water level return period values are higher for the same return period corresponding to rainfall. The bias between rainfall and water level return periods for the complete rainfall dataset indicate that for Point 1 there are rainfall intensities which are likely to produce flooding which are not included in the selection of the 35 events for Point 1. Results for Point 2 (Figure 8(b)) are more dispersed, and correlation between water level return period and rainfall return period is smaller if compared to Point 1. In that case, both approaches present similar results when considering the 35 events or the 35 years' dataset. Differences found between Figure 8(a) and 8(b) are mainly due to the implicit local flood response time for each point and ambiguous relation between rainfall intensity and water level.

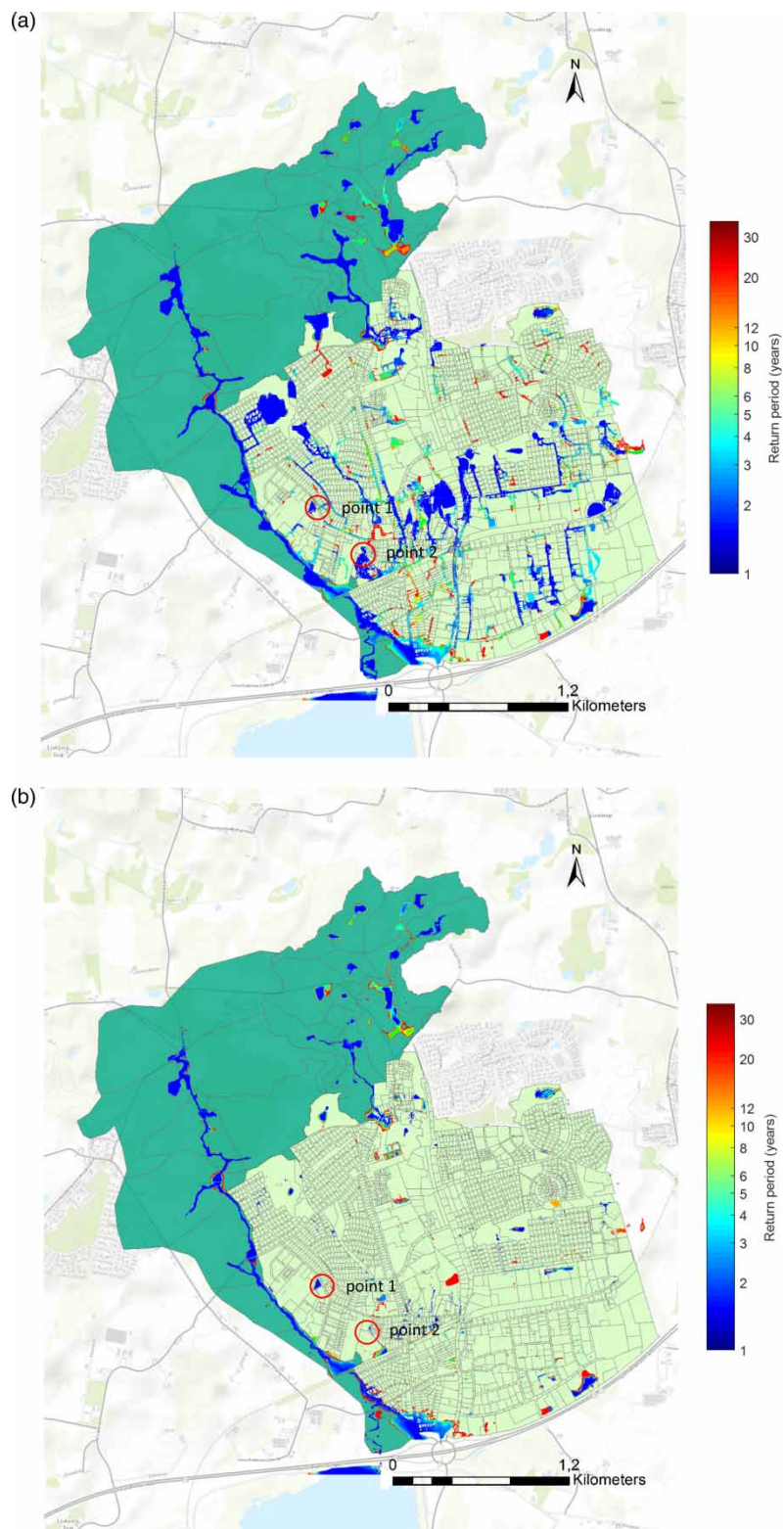


Figure 7 | Return period map of flood-prone cells for maximum water level of (a) 0 m and (b) 0.1 m.

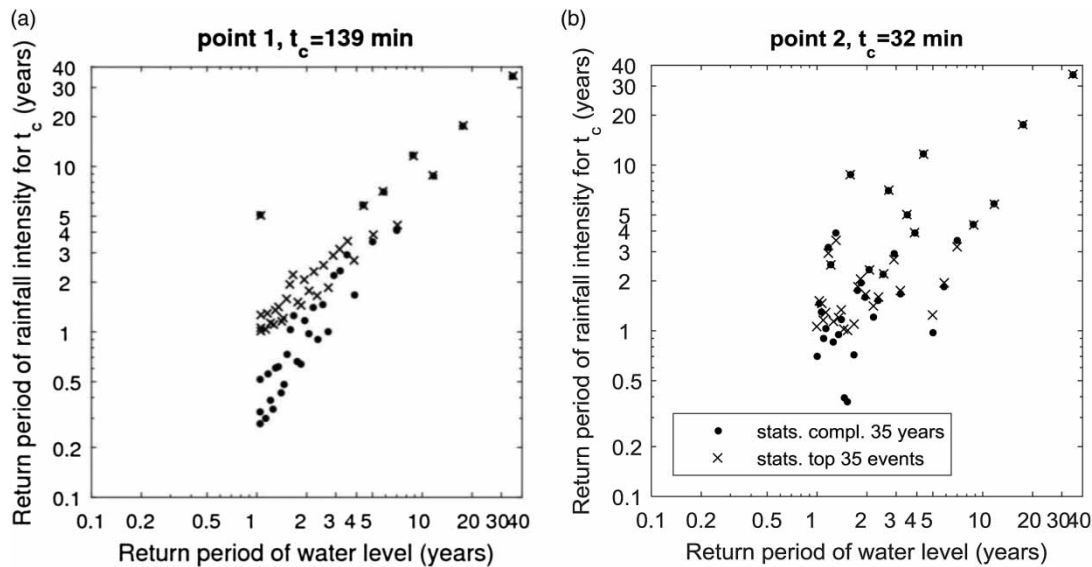


Figure 8 | Correlation between return period of water level and return period of rainfall for the derived critical time of concentration for (a) Point 1 and (b) Point 2.

As stated, the diverse analysis performed at Lystrup catchment emphasizes the need to apply a robust multiple approach for a precise flood return period assessment. In addition, a correct rainfall measurement, estimation, processing and analysis is necessary to better understand the principles of flood dynamics and the interactions associated with rainfall.

DISCUSSION

The various analyses performed in this study are intended to contribute with additional tools, that combined with the use of a more traditional approach, can upgrade the consistency and resiliency of future planning of complex urban drainage systems. However, the inclusion of longer temporal rainfall time series as well as incorporating spatial variability (e.g., X-band or C-band radar data estimates; Thorndahl *et al.* 2017a) should be considered in future studies. Statistics and uncertainties derived from rainfall measurements or estimates, as well as the ones derived from urban drainage system development and modelling, can have a large impact on any analysis performed over complex urban drainage systems, especially if the assessment is focused on flooding, thus they should also be a subject to consider in further studies (Deletic *et al.* 2012). Moreover, results

obtained in this study have underlined the importance to consider return periods from flooded areas, volumes and also local water levels to maximize rigor of flood return period assessment. Furthermore, climate change should also be considered in further analysis in order to build resilient urban drainage systems against flood, together with the continuous and active involvement of decision-makers and different stakeholders.

CONCLUSION

Obtained results from the flood return period assessment at catchment scale highlight that coupled 1D/2D models are essential since they are able to outline the different interactions between drainage system, runoff and surface flow dynamics. Moreover, flood area and volume return periods should be incorporated in the analysis and should be considered separately in order to guarantee the quality of results.

Inclusion of temporal dynamics of rainfall by estimating local flood response time over the flood-prone areas, as a surrogate measure of the time of concentration, has illustrated its potential impact on the urban drainage system. The assumed relationship between rainfall intensity and its monotonical increasing relation on flood levels is not

always applicable and very much depends on the urban drainage system complexity. In addition, appropriate rainfall selection and the temporal dynamics of rainfall have been widely referred to as a key element when performing such kind of analysis.

Return period analysis performed under a local perspective has shown that identification of flood-prone areas can be crucial for a better understanding of surface flood dynamics. It allows initially focusing on the areas where most attention is needed and consequently increasing the adequacy of storm water management of urban drainage systems under heavy rainfall.

Although the performed flood return period assessment has shown promising results, it is important to state that it only refers to one specific case study. Therefore, specifics of the applied approach throughout this paper should be reconsidered for other catchments or study areas.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the ERA-NET Cofund Water Works 2014 (project MUFFIN) for the partial funding of this research; the Danish Wastewater Pollution Committee and the Danish Meteorological Institute (DMI) for providing the rainfall dataset; the Danish Geodata Agency for providing the DTM data, DHI for providing the licence to MIKE software packages and Mrs Laura Casas for her cooperation in this study. The applied model has been made available for this study by Aarhus Water utility services.

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